

Final Report-Global assessment of volcanic debris hazards from space

Research Summary

Hazard (slope stability) assessment for different sectors of volcano edifices was successfully obtained from volcanoes in North and South America. The assessment entailed Hyperion images to locate portions of the volcano that were hydrothermally altered to clay rich rocks with zones that were also rich in alunite and other minerals. The identified altered rock zones were field checked and sampled. The rock strength of these zones was calculated from the field and laboratory measurements. Volcano modeling utilizing the distinct element method and limit equilibrium technique, with the calculated strength data was used to assess stability and deformation of the edifice. Modeling results give indications of possible failure volumes, velocities and direction. The models show the crucial role hydrothermally weak rock plays in reducing the strength of the volcano edifice and the rapid identification of weak rock through remote sensing techniques. Volcanoes were assessed in the Cascade Range (USA), Mexico, and Chile (ongoing).

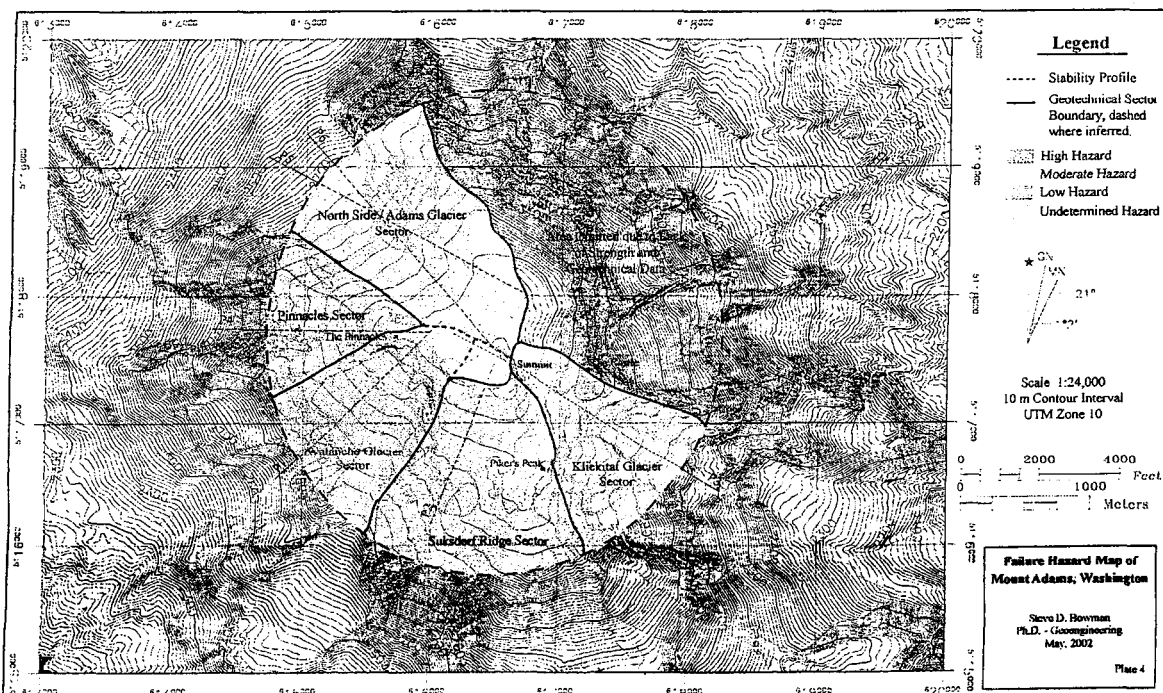


Figure 1. Failure hazard map, Mt. Adams, Washington State, (Bowman, Ph.D., 2002)

Papers published: One paper published, 36th. Annual Engineering Geology and Geotechnical Engineering Symposium.

Abstracts published: Six abstracts at AGU and the AEG conferences.

Papers submitted: One paper under review with Bulletin of Volcanology and another (invited) to the Bulletin of Environmental and Engineering Geoscience (GSA).

Graduate students: Two graduate students funded, one awarded Ph.D. the other an MS degree in geological engineering. Both research topics on volcano hazards.

Global Assessment of Volcanic Debris Flow Hazards from Space

Background

This project is the volcanic failure hazards portion of the overall project scope. Remote sensing data from the other PI (Jim Crowley - USGS) identified areas on the volcano with altered rock, which directed the geotechnical portion to sample these areas for strength and slope stability/hazard appraisal. Volcanoes were assessed from the Cascade Range (Adams, Mt. St. Helens, and Mount Shasta in the USA, Pico de Orizaba, Mexico, and in Chile (San Pedro, Azufre, Lascar, and Socompa). The research is ongoing, though the fieldwork is complete.

Assessing sector or flank instability requires that a geological model be constructed which characterizes both the internal geologic structure and rock mass strength. In an oversimplified form, this would be a pile of sand at the angle of repose and all sectors of the sand pile would have a similar risk of failure, given the isotropic nature of the material strength and geologic structure. However, a volcano is not a pile of sand. Consequently, a volcano can not be regarded as being isotropic in all direction from a geologic or rock strength perspective. Slope stability of the cone is dependent on the strength of volcanic materials, topography, and the influence of seismic forces and fluid pressure. A key component therefore in edifice stability is the assessment of edifice rock mass strength, its variability and spatial distribution. Weak, highly altered and clay rich rocks are often found in landslide and lahar deposits, and strongly suggests that weak hydrothermally and clay rich rocks within the edifice, play a crucial role in localizing catastrophic sector and flank collapse to specific portions or sectors of the volcano. The delineation of weak zones on the volcano, which typically are the lahar and landslide sources, requires the edifice to be zoned to reflect the changes in rock mass strength and geologic structure.

Data Collection

Edifice strength assessment required a geologic and geotechnical mapping program. The program required identifying areas of the volcano from processed Hyperion data that showed altered areas of rock. Thereafter, fieldwork was comprised of two components. The first part was to obtain rock structure information, which permits the degree of fracturing throughout the volcano to be assessed. This assessment included the systematic collection of joint and bedding orientations, joint and fracture spacing, together with locating the position of major shear and fault zones cutting at or near the edifice. Figure 2 details the locations and rock fracture orientations for Mount Shasta, California. The second part consisted of the collection of representative edifice and flank materials from which the full range of intact rock strengths, strength of rock joints and infilling material, and the type and alteration intensity of the collected specimens could be ascertained. Once this data was collected, the strength of individual portions of the edifice was determined, taking into account the effects of hydrothermal alteration on rock strength. It was therefore possible to quantify the strength reduction for individual portions (or sectors) of the volcano, and the strength of particular joint sets and/or shear zones. The

subsurface geology was developed utilizing generalized geologic cross-sections, from surface mapping, headwall mapping, and from mineralogical, isotopic, and geochemical results.

The geotechnical phase of the study concentrated on obtaining samples of the weakest exposed rocks from selected volcanoes. The weakest rocks are generally those that have been hydrothermally altered and/or closely fractured and sheared. This required obtaining altered rock samples from the crater rim and cone flanks of the volcanoes, and fracture mineral infilling, and altered joint and bedding surfaces. Particular attention was directed at obtaining rock samples from fracture systems at the summit, which can provide major planes of weakness, and can act as release boundaries for potential failure masses. Strength characterization of these surfaces is important for stability analysis. Rock shear strength, intact rock strength, and density tests were performed on all the samples, enabling a range of values to be determined which characterized the strength of the volcano's cone. Structural information was obtained at the rim to provide stereoplots of joint sets and bedding attitudes.

The field and laboratory rock strengths for samples collected from Pico de Orizaba are summarized in Tables 1 and 2. The tables illustrate the range in strengths as a function of the intensity of alteration and density. In general, hydrothermal alteration produces a lower density rock, with a corresponding reduction in strength, which can be seen in the unconfined compressive strength results of Table 1. The greater the intensity of alteration the lower is the strength. The shear strength testing of joints and bedding surfaces contained in Table 2, established an envelope of shear strength and stiffness values for joint and bedding surfaces within the cone, which reflect different alteration intensities and mineralization. The measured and calculated rock strength values of friction angle and cohesion, show that the lowest strengths occur in altered rock, and along individual altered joints and bedding. The strength results show that anisotropic rock mass strength exists at the edifice, with sectors of the summit comprised of large weak rock masses, bounded by steep to vertical fracture systems, that sit on outwardly dipping lava flows. Many of these fracture systems and bedding surfaces are highly altered, with their surfaces coated with kaolinite and/or alunite. In addition extensive areas of massive alteration exist, up to meters thick, with very low rock strength and densities.

Table 1 Summary of unconfined compressive strength for fresh and altered andesite

| Alteration Grade | Rock Density g/cc | Average Strength MPa | Standard deviation MPa | Strength Range MPa | Number of Tests (n) |
|------------------|-------------------|----------------------|------------------------|--------------------|---------------------|
| Unaltered | 2.5 | 146 | 43.4 | 196 - 120 | 15 |
| 2 - 4 | 1.7 - 0.8 | 34.7 | 17.4 | 57.8 - 8.6 | 32 |

Table 2 - Summary of shear strength from shear zones, and joint and bedding surfaces for andesite.

| Alteration Intensity | Alteration Type | Rock Density of Surface g/cc | Friction Degrees | Cohesion Mpa | Shear Stiffness MPa/m x 10 ³ |
|----------------------|-----------------------|------------------------------|------------------|--------------|---|
| 0 | Unaltered | 2.5 | 34 | 0.96 | 17.93 |
| 1 - 2 | Kaolinite and Alunite | 2.4 | 39 | 0.21 | 2.76 |
| 3 - 4 | Kaolinite and Alunite | 1.04 | 24 | 0.07 | 0.49 |

Modeling Studies

Modeling studies are a crucial part in volcano stability assessment as they show how changes in rock strength and/or internal geologic structure can affect volcano slope stability. Models can be developed which can show which portions (or sectors) of the volcano may be the first to collapse due to the reduction of rock mass strength from hydrothermal alteration and the influence of seismic or eruptive forces. Previous modeling studies using either limit equilibrium or numerical methods provide insights into volcano deformation and catastrophic collapse. If edifice and/or flank failure is very recent or on going and can be monitored as at Montserrat Volcano, sample collection and rock strength testing combined with slope modeling, provides critical insights into failure process and the factors associated with collapse.

In modeling Pico de Orizaba, the most insightful method of stability modeling, where no previous failure has been mapped or identified was by numerical methods as opposed to a limit-equilibrium approach. Numerical modeling permits movement of the slope to be investigated at different depths below the volcano surface and provides observations of failure processes by imputing different rock strengths and geologic structure into the model. The limit-equilibrium method does not provide displacement information throughout the slope but yields a factor of safety for the entire slope by determining the critical slip surface. The combination of insitu field strength data, and laboratory testing provides the input to numerical modeling to assess the complexity of volcano failure mechanisms. The use of computer program UDEC allows the influence of varying physical and mechanical properties to be investigated and provides accurate velocity and volume information which can be incorporated later into run-out models for use in hazard zonation. The modeling studies conducted as part of the project are most advanced for Pico de Orizaba and Mount Adams.

Utilizing the UDEC model required the input of internal geologic structural information, including joint and bedding orientations, strength along these surfaces, rock density, and topographic relief. This model incorporates the data obtained from fieldwork, aerial photography, and field and laboratory rock strength testing. The basic model of Pico de Orizaba is shown in Figure 3. Based on field observations and laser distance

measurements on the summit, a core width of 700 meters was incorporated into the model. The volcano core represents the weakest, most intensely altered, and heavily jointed rock of the volcano cone. In Figure 3, the distance between different joints and the distance between beds was fixed at 50 meters for the new cone, to enable block interactions and movement of the slope to be clearly observed. In the model failures were induced with block sizes (bed and joint separation distance) ranging from 10 to 100 meters apart, though most stability runs were at between 25 to 50 meters. At small joint and bedding separations computer run times are excessive and block interactions are difficult to observe. The rock material underlying the new cone is constructed with a greater distances between joints and bedding, 100 to 200 meters separation, to easily distinguish between the different cones.

After construction of the model and selecting cross-sections through the volcano, the next most critical decision is the selection of field and laboratory strength values from Tables 1 and 2. The selected values were generally at the lower end of the calculated strengths and are summarized in Table 3.

Table 3 Strength data used for modeling studies

| Description | Rock Density g/cc | Friction Degrees | Cohesion MPa | Shear Stiffness MPa/m x 10 ³ |
|-------------|----------------------|---------------------|-----------------|--|
| Core | 1.6 | 10 | 0.07 | 100 |
| New Cone | 2.5 | 20 | 0.14 | 100 |
| Contact | 1.6 - 2.0 | 10 - 15 | 0.07 - 0.10 | 100 |
| Older Cone | 2.5 | 30 | 0.45 | 1000 |

Volcano stability results

Various cross-sections were analyzed through the new cone but the most critical orientation for the cross-section was contained between the east - west and southeast - northwest sections. This sector of the cone, between the east and southeast portion, consistently failed when low rock strengths were incorporated into the model. Cross-sections in these sectors contain most of the altered rock and steepest topography.

The model uses only one north - south striking joint set, dipping steeply to the west, Figure 3. Designating a low alteration strength for jointing and bedding, and the lowest strength for the core, the rock mass surrounding the crater core displaces in an easterly direction as an "intact block" during the first ten seconds, failing along the bedding and joint surfaces. The removal of support to the core produces an initial toppling failure mode Figure 4. Continuing displacement transforms the "intact block" and the toppling mass into a chaotic mass of individual blocks some 40 seconds after the initial failure, Figure 5. The displacement and velocity of individual blocks within the failing mass can be analyzed. Figure 6 shows the time-velocity plot for one individual block in the center

of the initial "intact block". After approximately 20 seconds the block is moving at about 40 meters per second increasing in velocity at uniform rate. Between 20 and 50 seconds the velocity increase slows down, falling into a range of between 60 to 75 meters per second. The abrupt changes in velocity are a result of block collisions, reducing or increasing the velocity, as the initial "intact block" breaks-up into a chaotic mass of individual blocks, with their own time-velocity histories. Characteristic morphologic features of edifice collapse can be observed as in Figure 5, with the crater now containing a steep head wall.

Conclusions

Identification of hydrothermally altered rock on volcanoes using Hyperion data permits site specific sampling to be performed for rock strength and alteration products. Subsequent slope stability modeling has shown that failure of a volcano typically occurs in weak hydrothermally altered argillic rock. The failure modes and volumes are dependent on the internal structure of the volcano and strength values selected for different portions of the volcano. Instability can be induced by alteration of lava flows, the subsequent lower strength producing the overlying rock to fail and slide along the outwardly dipping bed(s). Incorporating steeply dipping joint sets, combined with the outwardly dipping flows, permits failure of the outer portion of the cone as an "intact block". As the failure progresses, more of the inner core fails as the outer "intact" block transforms into a collection of smaller blocks, increases in velocity, and may transform into a debris-flow. Eventually a steep face is produced where the uppermost portion of the core existed. This type of morphology is often seen after edifice failure.

Velocities of the sliding mass typically range from 30 to 75 meters per second after some 45 to 60 seconds from failure initiation. Failure volumes range from a low of 40 million cubic meters to a high of about 200 million cubic meters (0.04 - 0.2 cubic kilometers) for small failures, and up to 2.0 km³ for a large catastrophic failure. Failure volume reflects the depth of the alteration below the volcano surface and especially for small failures the orientation of major structures. Combining rock strength with the slope stability modeling permits the volcano to be zoned to show what part (or sector) has the greatest chance of failing in the event of an eruption or earthquake. This can be shown on a hazard map of the volcano. Mount Adams was the first volcano that a failure hazard map was developed, based in part on geotechnical data. Smaller failures can occur without eruption or earthquake forces and may be triggered by abnormal precipitation events. Future refinements would include using the failure hazard map with radar interferometry (InSAR) measurements from airborne and spaceborne sensors. This would be a method of recognizing regions of potential sector failure in real-time in the event of volcano unrest, and improve hazard analysis and potentially reduce the risk to nearby communities.

Additional papers published:

Zimbelman, Watters, Bowman, Firth. (2003) Quantifying Hazard and Risk Assessments at Active Volcanoes. EOS, Vol. 84, No. 23, pp. 213 – 217.

Zimbelman, Watters, Firth, Breit, Carrasco-Nuez, (2003) Stratovolcano stability assessment methods and results from Citlaltepēt, Mexico. *Bulletin of Volcanology*, Volume 65.